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Testing predictive control of movement in children with developmental coordination disorder using converging operations

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Recent systematic reviews (Wilson *et al.*, 2013, *Dev. Med. Child Neurol.*, 55, 217; Adams *et al.*, 2014, *Neurosci. Biobehav. Rev.*, 47C, 225) suggest that a common underlying problem in developmental coordination disorder (DCD) is the internal modelling deficit. The study presented here is the first to test this hypothesis using a within-subject design, assessing motor imagery, action planning, and rapid online control (ROC) in a sample of children screened rigorously for DCD. Participants were 66 children; 33 children (26 boys and seven girls) aged 6–11 years in the DCD group and 33 controls (gender and age matched). Motor imagery was assessed with the hand rotation task (HRT), action planning with an end-state comfort effect test, and ROC with the double-step pointing task. Results showed that children with DCD were slower and less accurate than controls in the HRT. Reduced forward planning for comfortable end-state was also shown in DCD. Finally, no group differences were found on the ROC task. Collectively, children with DCD manifest deficits in the internal modelling of movements, but this varies under different task constraints, particularly those related to movement complexity.

Skilled motor behaviour is seen as the ability to produce fluid, well-coordinated, and efficient movements, often in the face of dynamic environmental conditions. In particular, the ability to adjust movements seamlessly during the course of action is a vitally important aspect of control, one based on the capacity of the motor system to learn its own dynamics and thence to model its own 'behaviour' in real time; this enables the performer to make online adjustments (to force and spatiotemporal parameters) based on forward estimates of limb position (Flanagan, Vetter, Johansson, & Wolpert, 2003; Shadmehr, Smith, & Krakauer, 2010). Deficits in this process of forward (or internal) modelling have been linked to children with motor coordination problems (or developmental coordination disorder – DCD).

Children with DCD fail to develop levels of skill that are commensurate with the expectations of age and previous opportunities for skill learning. This can manifest as problems with fine motor skills (e.g., holding a pencil and writing, cutting with scissors), gross motor skills (throwing and catching a ball, riding a bicycle), balance, or a combination of skills that interfere with activities of daily living or academic achievement (American Psychiatric Association, 2013). There is now a significant body of work into the

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aetiology of DCD which reveals a number of viable hypotheses including reduced processing speed, problems in executive functioning, poor cross-model integration, and poor perceptual-motor coupling (for review see Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). In two recent systematic reviews, this collective evidence was analysed (Adams, Lust, Wilson, & Steenbergen, 2014; Wilson *et al.*, 2013) to reveal a prime underlying deficit in motor control and learning linked specifically to the predictive control of movements. This deficit has also been described as the ‘internal modelling deficit’ (IMD; Wilson & Butson, 2007; Wilson *et al.*, 2013).

The concept of an internal model is a unifying one, explaining basic mechanisms of both motor control and learning (Wolpert, 1997; Wolpert & Kawato, 1998) within a computational neuroscience framework (Kawato, 1999). The importance of forward (or predictive) estimates of limb dynamics and trajectory to the realisation of motor control has been validated in numerous behavioural studies (Boyle, Kennedy, Wang, & Shea, 2014; Houde & Borst, 2014; Olofsson, 2014; Shadmehr *et al.*, 2010). Predictive models contribute to volitional control and the stability of the motor system by anticipating the sensory consequences of a given movement. This internal prediction (or emulation) occurs before slow, sensorimotor feedback becomes available (Wolpert, 1997), providing a means of rapid online correction. When a motor plan is initiated, the motor cortex generates a motor command that is relayed to the body via descending corticospinal tracts. An efference copy of this motor command is generated in parallel as a corollary discharge and relayed to parietocerebellar and parietofrontal networks. These networks support a process of comparison between predicted estimates of limb dynamics and that provided by real-time sensory feedback (Bubic, von Cramon, & Schubotz, 2010). Errors of prediction are used as an input signal to modulate the ongoing action plan, with a latency that is far more acute than that possible via sensory feedback-based control (Hyde & Wilson, 2011a, 2013). Importantly, this process of control and error correction also generates training signals that can fine-tune forward planning over repeated trials or learning experiences.

While deficits of predictive control in DCD have been shown across a number of studies (Wilson *et al.*, 2013), before 2014, there has been no single study that has investigated different aspects of this mechanism in the same group of children (Adams *et al.*, 2014). Aspects of motor imagery, action planning, and rapid online control (ROC) have been investigated experimentally, but in separate groups of children (reviewed in Adams *et al.*, 2014). These studies differed on aspects of inclusion (research or clinical criteria) and examined the aspects of predictive control in isolation (motor imagery, action planning, ROC) as a consequence of which comparison among studies remained problematic. Two recent studies have examined motor imagery and action planning (Noten, Wilson, Ruddock, & Steenbergen, 2014) and motor imagery and ROC (Fuelscher, Williams, Enticott, & Hyde, 2015) using a single group of children with probable DCD. In this study, we assess three aspects of predictive control in a single DCD group that conform strictly to the DSM-V diagnostic criteria. By using a suite of experimental tasks that tap different aspects of internal modelling, using a within-subject design, we provide the strongest test to date of the IMD hypothesis. This advances our knowledge about underlying mechanisms of motor control that may be compromised in children with DCD, which is currently not well understood (Blank, Smits-Engelsman, Polatajko, & Wilson, 2011).

First, motor imagery tasks are considered a valid and valuable means of describing the content of internal models for movement (Decety & Grezes, 1999; Sirigu *et al.*, 1995). Earlier studies of motor imagery in DCD have employed two main paradigms: mental

rotation and mental chronometry. In mental rotation tasks (Parsons, 1994; Shepard & Metzler, 1971), participants have to make judgements on the laterality or identity of stimuli (e.g., hands, letter stimuli) displayed at different angles of rotation. For limb-related stimuli, use of motor imagery is inferred when the biomechanical constraints of the simulated movement are reflected in the pattern of response time or error data such as longer reaction times for laterally orientated stimuli than for medially orientated stimuli (Parsons, 1994; ter Horst, van Lier, & Steenbergen, 2010). Likewise, in the Visual Guided Pointing Task (VGPT) and the radial VGPT (Caeyenberghs, Wilson, van Roon, Swinnen, & Smits-Engelsman, 2009), mental chronometry between mentally imagined and real actions is taken as evidence for the use of motor imagery. In a recent systematic review (Adams *et al.*, 2014), we showed that motor imagery is impaired in children with DCD. In mental rotation, the deficit was shown by slower and less accurate performance in the DCD group relative to controls (Deconinck, Spitaels, Fias, & Lenoir, 2009; Williams, Thomas, Maruff, & Wilson, 2008) and a weaker trade-off between response time and rotation angle (Williams, Omizzolo, Galea, & Vance, 2013; Williams, Thomas, Maruff, Butson, & Wilson, 2006; Wilson *et al.*, 2004). In the mental chronometry task, this was manifest as a weaker correlation between real and imagined action and a trade-off between response time and task difficulty that was only preserved for real actions and not imagined (Ferguson, Wilson, & Smits-Engelsman, 2015; Lewis, Vance, Maruff, Wilson, & Cairney, 2008; Williams *et al.*, 2013; Wilson, Maruff, Ives, & Currie, 2001). In the study presented here, we used the hand rotation task to examine the motor imagery ability in DCD. The hand rotation task is regarded as a measure of implicit motor imagery (hence, not requiring explicit verbal instructions), thought to be more sensitive to age-related change, and has shown excellent construct validity for use in developmental studies (reviewed in Spruijt, van der Kamp, & Steenbergen, 2015).

Second, action planning tasks provide a window to both the content of the internal model and the execution of this model. Wolpert, Ghahramani, and Jordan (1995) showed that an estimation of the future location of the hand could be obtained by combining efferent and afferent signals in a forward model. Action planning tasks are used to examine how accurately the end-state of a movement is predicted, based on the forward model (Johnson, 2000; Steenbergen, Jongbloed-Pereboom, Spruijt, & Gordon, 2013). Earlier research point to a causal link between motor imagery and planning for end-state comfort (ESC): (1) similar neural structures are activated during imagery of end-state postures and the actual planning of a movement (Hanakawa, Dimyan, & Hallet, 2008; Lacourse, Orr, Cramer, & Cohen, 2005), and (2) for post-stroke patients, motor imagery training is reported to have beneficial effects on motor rehabilitation (Page, Levine, & Khoury, 2008; Sharma, 2006). We define action planning as the ability to take into account the goal of the task when first taking hold of an object (Johnson-Frey, McCarty, & Keen, 2004). The forward planning process is apparent when participants plan for ESC even when they have to sacrifice initial comfort (Rosenbaum *et al.*, 1990). Studies examining the ESC effect in children with DCD showed conflicting results. van Swieten *et al.* (2010) showed that children with DCD were biased towards selecting the simplest initial posture, indicating reduced forward planning. Smyth and Mason (1997) and Noten *et al.* (2014), however, showed no difference in grip selection between a DCD and a control group. In earlier studies, the difference in performance on several tasks examining the ESC effect has been compared and contrasted (Jongbloed-Pereboom, Spruijt, Nijhuis-van der Sanden, & Steenbergen, 2016; Knudsen, Henning, Wunsch, Weigelt, & Aschersleben, 2012; Smyth & Mason, 1997). In the study of Jongbloed-Pereboom *et al.* (2016), it was shown that the sword task is a more complex task than the bar grasping task. In the critical

orientations of the sword task participants have to move their hand in a lateral position, which demands an ulnar deviation of the wrist, an orientation that is perceived as less comfortable (Parsons, 1987). In addition, at the end of the task, the precision demands are higher for the sword task. The test–retest and inter-rater reliability of this task were shown to be good (Jongbloed-Pereboom, Nijhuis-van der Sanden, Saraber-Schiphorst, Crajé, & Steenbergen, 2013). In this study, we used the sword task to examine the action planning in children with DCD and a control group, because we expected that the increased level of complexity of this task would be more sensitive to age- and group-related differences.

Third, the online control of movements requires that the motor system predicts the future location of the moving limb using a forward internal model (Desmurget & Grafton, 2003; Jeannerod, 2006; Wolpert, 1997). Recently, it was shown that motor imagery ability was a significant predictor of the ability to implement online (reach) corrections in healthy adults (Hyde, Wilmut, Fuelscher, & Williams, 2013) and children with DCD (Fuelscher *et al.*, 2015). This forward estimate of limb position permits the rapid integration of efferent and afferent signals, speeding perceptual-motor responsivity (Desmurget & Grafton, 2003). In the case of target-directed reaching, the nervous system must implement rapid changes in trajectory, in-flight, should movement be perturbed in some way or in the event of a visually detected change in the environment. Online corrections of this type depend on an individuals' ability to compare the predicted sensory consequences of a prospective action (based on the forward internal model) and actual sensory feedback (Izawa & Shadmehr, 2011; Shadmehr & Krakauer, 2008; Wolpert, Diedrichsen, & Flanagan, 2011). Experimentally, the operation of these internal feedback loops has been examined in children with DCD using double-step perturbation paradigms (Hyde & Wilson, 2011a,b, 2013; Plumb *et al.*, 2008). Children with DCD were repeatedly shown to exhibit a reduced ability to correct movements in flight (Fuelscher *et al.*, 2015; Hyde & Wilson, 2011a,b, 2013; but see Plumb *et al.*, 2008), evidenced by longer movement times (MTs) in response to target perturbation and later changes in trajectory. These findings indicate that visual perturbations are detected more slowly and/or internal feedback loops operate with higher levels of neural noise (Smits-Engelsman & Wilson, 2013). In this study, children performed double-step reaching using (2D) finger sliding movements on a touch screen and not (3D) lift-and-touch movements. This set-up provided the flexibility needed to conduct home-based measurements as no advanced 3D kinematic system was needed. The 2D registration has been shown to be valid and reliable in earlier studies (Henis & Flash, 1995; van Sonderen, Gielen, & Denier van der Gon, 1989). We chose to use the finger and not a pen or stylus as the touchpoint on the screen because handwriting problems are well known in children with DCD (Prunty, Barnett, Wilmut, & Plumb, 2013; Rosenblum & Livneh-Zirinski, 2008).

Taken collectively, the evidence thus far suggests deficits in predictive control in children with DCD. The next step is to examine the performance on these tasks coherently within one group of children with DCD. In this study, we tested 33 children with DCD (according to the DSM-V criteria) and 33 age-matched controls on three tasks that assess specific aspects of the internal model. We used an age range from 6 to 11 years which is critical for the development of predictive control (Caeyenberghs *et al.*, 2009). To examine the content of the internal model, we used a motor imagery task, the hand rotation task. To test both the content and execution of the internal model, we used an action planning task, the 'sword' task (Crajé, Aarts, Nijhuis-van der Sanden, & Steenbergen, 2010; Jongbloed-Pereboom *et al.*, 2013). Finally, to examine the detection and correction of online perturbations, the double-step reaching paradigm was used.

Methods

Participants

Thirty-three children (26 boys and seven girls) between the ages of 6 and 11 years who met the DSM-V diagnostic criteria for DCD and 33 individual gender and age-matched controls (± 4 months) were included (American Psychiatric Association, 2013). The mean age for the DCD group was 8.89 ($SD = 1.40$), and 8.93 years ($SD = 1.36$), for the control. Fifty-nine children were right-handed, as indicated by their parents on the health questionnaire and indicated by the children when performing the manual tasks of the movement ABC-2 (m-ABC-2), and seven children (two DCD, five controls) were left-handed.

The DCD group was recruited through paediatric physical therapists and via an advertisement on a website for parents of children with DCD. The included children in the DCD group all met the following four inclusion criteria to ensure that the DSM-V diagnostic criteria for DCD were met: (1) m-ABC-2 (Dutch translation; Smits-Engelsman, 2010) total percentile score ≤ 16 th or component percentile score ≤ 5 th percentile (criterion A DSM-V), (2) treated or have been treated for a motor coordination problem by a paediatric physical therapist (criterion B DSM-V), (3) $IQ > 70$. If children attended regular primary education and had not been diagnosed with a learning disorder, an $IQ > 70$ was inferred. When children attended special education, IQ score was checked by asking their parents the latest IQ score (criterion D DSM-V), and (4) no visual impairments or neurological conditions that could affect their motor abilities (criterion D DSM-V). A health questionnaire with specific questions about medical conditions was used to ascertain this last criterion. Criterion C of the DSM-V about the early onset of symptoms is present because the children have symptoms between 6 and 11 years of age.

Children for the control group were recruited on two mainstream primary schools. Control children were included if they had a m-ABC-2 total percentile score > 20 th percentile and $IQ > 70$ (inferred when attending regular primary education and not been diagnosed with a learning disorder).

Procedure

Approval for the experiment was obtained from the local Ethical Committee (Registration number: 2013-1405-110a1). The parents of all participants signed a written informed consent form prior to the study and were asked to fill in the DCD-Q (Dutch translation; Schoemaker, Reinders-Messelink, & de Kloet, 2008), the ADHD questionnaire (ADHQ; Scholte & van der Ploeg, 2004), and a questionnaire concerning the health of their child. The DCD-Q was used to monitor the interference of the motor problem with activities of daily living and academic productivity (criteria B of DSM-V), and the ADHQ was used to examine signs of ADHD in both groups because ADHD often co-occurs in DCD. After receiving the informed consent and questionnaires, the child was asked to fulfill several tasks.

During all experimental tasks, participants were seated on a comfortable chair with their arms resting on the table in front of them. All participants performed the experimental tasks in the same order: (1) hand rotation task, (2) double-step reaching paradigm, and (3) sword task. The m-ABC-2 was assessed after the experimental tasks, and a break was provided in between the experimental tasks and the m-ABC-2 to prevent fatigue. Children needed 1 hr to complete all tasks. For the hand rotation task and double-step reaching paradigm, custom-developed software in the Presentation software package (Neurobehavioral Systems, Albany, CA, USA) was used to present stimuli and

record data. In the hand rotation task, a laptop screen (14-inch) was placed 60 cm in front of the participants. In the double-step reaching paradigm, a 19-inch touch screen (ELO 1928L Desktop Touchmonitor; Elo Touch Solutions, Milpitas, CA, USA) was placed in front of participants on a table and was tilted about 10° towards them.

Assessments

Motor imagery

Children were asked to determine whether the presented hand was a left or a right hand by pressing the corresponding button. Participants placed their hands on two separate buttons, with their palms down, and vision of the hands was occluded by a towel. The stimuli were custom-made 3D hand stimuli (length of hand stimuli on screen was 9 cm), designed in a 3D image software package (Autodesk Maya 2009, San Rafael, CA, USA). These stimuli were presented in six different orientations, starting at 0° (fingers pointing up) and rotated clockwise to 60° , 120° , 180° , 240° , and 300° , for both left and right hands, yielding a total of 12 different stimuli in back view and 12 different stimuli in palm view. In block 1, the back view stimuli were shown; in block 2, the palm view stimuli were shown. Stimuli were presented in a random order, and every stimulus was presented three times, resulting in 36 stimuli per block. Every block was preceded by 18 practice trials. Outcome measures were reaction times (RTs) – time between appearance of the hand stimulus and button press – and number of errors.

Anticipatory action planning

Action planning was assessed by a validated task to measure action planning in children (Craje *et al.*, 2010; Jongbloed-Pereboom *et al.*, 2013). Children had to pick a wooden sword (length 18.0 cm, width 2.0 cm, height 1.2 cm, handle length 9.5 cm) from the table and subsequently sting it into a tight hole (2.0×0.8 cm) of a ‘treasure chest’ (a wooden block of $27.0 \text{ cm} \times 13.0 \text{ cm} \times 13.0 \text{ cm}$). The sword was always presented on a sheet of paper (30 cm length and 28 cm width) on which six possible sword rotations and the fixed position of the treasure chest were drawn (see Figure 1a). Four of these six

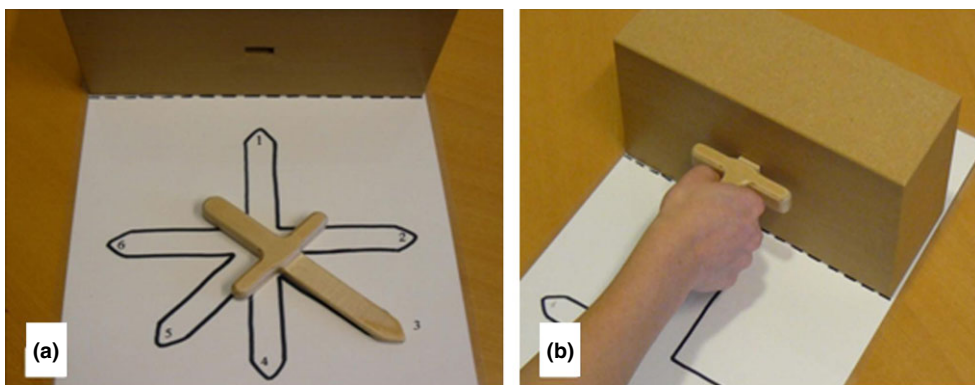


Figure 1. (a) Set-up of the action planning task, sword in orientation 3. The sword orientation with the blade towards the wooden block was designated as Orientation 1. (b) Example of a comfortable end posture.

starting orientations served as the control orientations, and two served as the critical orientations. In these critical orientations, children needed to sacrifice comfort of the start posture in order to be able to end the task in a comfortable posture on fitting the sword into the tight-fitting hole (orientations 2 and 3 for right-handed participants, orientations 5 and 6 for left-handed participants). Children were instructed to pick up the sword with a power grip (i.e., whole hand grip) with their dominant hand and subsequently place it in the tight-fitting hole in the treasure chest (Figure 1b). The experiment always started with a trial that did not require any sword rotation (Orientation 1). After successful completion of this trial, the experiment started. Every rotation was repeated three times resulting in a total of 18 trials, presented in random order. The experimental session was recorded with a digital video camera for offline data analysis. The percentage of comfortable end postures in both the critical and the control orientations served as the dependent variable of interest. In the study of Jongbloed-Pereboom *et al.* (2013), it was shown that this task has good test–retest and inter-rater reliability, with intraclass correlation coefficients of .90 and .95, respectively.

Rapid online control

To assess ROC, the double-step reaching paradigm was used. The display on the touch screen consisted of a white circle at the bottom centre of the monitor, the ‘home base’ (diameter 20 mm), and three possible white target locations (each 20 mm in diameter) in a semi-circular formation across the top of the screen. The distance between the centre of the home base and each target was 25 cm, and the targets were spaced 20° apart at the coordinates of –20°, 0°, and 20° with respect to the home base. Participants were asked to perform the task by using the index finger of their dominant hand. At the beginning of each trial, the home base and the middle target were shown. The children were instructed to touch and hold the home base with their index finger. After a random interval between 500 and 1,000 ms, a beep tone was emitted; then, participants had to touch the target circle as quickly as possible by making a sliding movement on the touch screen. In 75% of the trials, the middle target had to be hit, while in 25% of trials, the middle target suddenly jumped either to the position –20° or +20° with respect to the home base at the moment the participant had left the home base. After touching the screen within the designated target boundaries, the child was instructed to return to the home base and wait for the next target. Prior to the performance of the task, the children were given four practice trials. The participants then completed two blocks of 32 trials. The blocks were separated by a short break. Each block consisted of 24 non-jump trials and eight jump trials (4 to each side) which were presented in a pseudorandomized order.

Data analysis

All analyses were performed using SPSS version 19 (IBM Corp, Armonk, NY, USA). Alpha level was set at .05, and Greenhouse–Geisser corrections were performed when the assumption of sphericity was violated. The total score on the ADHDQ was first entered to all repeated-measures ANOVAs and checked whether the covariate had a significant effect. When the covariate had a no significant effect, it was removed from the analysis and results of the model without the covariate are then reported.

Questionnaires

Total score on the DCDQ and ADHDQ was compared between the DCD and control group with two independent *t*-tests. Total score on the ADHDQ was first entered to all repeated-measures ANOVAs of the hand rotation task and ROC and checked whether this covariate had a significant effect.

Motor imagery

Mean response times (RTs) and number of errors were calculated for each angle of rotation and for each condition. Anticipatory responses (<250 ms) and RTs showing an abnormal delay ($>3.0 \times SD$ above mean RT per condition per individual) were removed before subsequent analyses (1.9% and 2.1% in the back view for control and DCD group, respectively, and 1.9% and 3.6% in the palm view for control and DCD group, respectively). In addition, only children that had at least half of all trials (≥ 18 trials) correct were included in the analysis. This was considered separately for the back (included, DCD group: 30; control: 33) and palm view condition (included, DCD group: 30; control: 33). For back and palm view, two separate repeated-measures ANOVAs (2 [groups] $\times 6$ [rotation angle] $\times 2$ [left/right-hand stimuli]) with RT as dependent variable were conducted. To infer use of motor imagery, the RTs of lateral (60 R, 120 R, 240 L, and 300 L) and medial (60 L, 120 L, 240 R, and 300 R) stimuli were compared within a 2 (groups) $\times 2$ (lateral/medial) repeated-measures ANOVA (Jacobsen, 2014). The number of errors were analysed with a Mann–Whitney *U*-test.

Anticipatory action planning

For the sword task, the percentage of comfortable end postures in critical and non-critical trials of the sword task were compared between DCD and control group with a Mann–Whitney *U*-test.

Rapid online control

Mean MT (duration between leaving the home base and reaching the target circle) and mean total time (TT; duration between the start beep and reaching the target circle) were calculated for both conditions (non-jump/jump) for each individual. Outliers ($>3.0 SD \pm$ the mean MT or TT per condition per individual) and anticipatory responses (trials in which half of the distance between home base and target (25 cm) on the touch screen was reached within <100 ms following the start signal) were discarded from analysis (11.7% in the DCD group, 13.48% in the control group). Two repeated-measures ANOVAs (2 [Group] $\times 2$ [Condition: jump/non-jump]) were conducted on mean MT and TT. Independent *t*-tests were conducted on MT_{diff} and TT_{diff} to compare the DCD and control group. Centre touch errors (CTEs) were examined with a Mann–Whitney *U*-test. Using a 2D (x by y) representation of each reaching trajectory for jump trials, the path length for each jump trial was calculated using the formula $\sqrt{(\Delta x^2 + \Delta y^2)}$. Mean path lengths for each participant on jump trials were then calculated. An independent *t*-test was used to examine whether path lengths on jump trials significantly differed between the DCD and control group.

Results

A summary of the group effects on all experimental tasks and interactions involving group can be found in Table 1.

Questionnaires

In line with our expectations, total scores on the DCD-Q were lower for the DCD group ($M = 37.06$, $SD = 13.29$) than the control group ($M = 65.39$, $SD = 9.96$), $t(64) = -9.98$, $p < .001$. Total scores on the ADHDQ were higher for the DCD group ($M = 25.48$, $SD = 13.95$) than the control group ($M = 13.33$, $SD = 12.49$), $t(64) = 3.73$, $p < .001$. The health questionnaires showed that three children in the DCD group had a formal diagnosis ADHD (assessed by a health professional), as well as two children in the control group. In initial analyses, total score on ADHDQ was entered as a covariate in all ANOVAs. However, the effect was not significant in any of the analyses and we therefore removed ADHDQ as a covariate from all ANOVAs.

Motor imagery

Because the RTs in the hand rotation task were not normally distributed, all RTs were transformed using a log10-transformation.

The 2 (groups) \times 6 (rotation angle) \times 2 (left/right-hand stimuli) ANOVA for the back view revealed that the DCD group had larger RTs than the control group, but this just failed to reach significance, $F(1, 61) = 3.72$, $p = .058$, $\eta^2 = .057$. RTs significantly differed per rotation angle, $F(4.53, 246.64) = 63.03$, $p < .001$, $\eta^2 = .51$ (see Figure 2). There was no significant difference in RTs between left- and right-hand stimuli ($p = .39$). A significant rotation angle*group interaction was found indicating that increase in RT per rotation angle was larger in the control than in the DCD group, $F(4.04, 246.64) = 2.68$, $p = .022$, $\eta^2 = .04$ (see Figure 2a). When running two separate 6 (rotation angle) \times 2 (left/right-hand stimuli) ANOVA for DCD and control group, it was shown that RTs significantly differed per rotation angle in both groups, but that the effect size was larger in the control group, DCD: $F(1.44, 2.26) = 18.44$, $p < .001$, $\eta^2 = .39$, control: $F(3.39, 2.14) = 50.81$, $p < .001$, $\eta^2 = .61$. There was a significant rotation angle*left/

Table 1. Group effects on all experimental tasks

Task	Dependent variable		Group effect	Significant interactions with group
Hand rotation	Reaction times	Back	$p = .058$, $\eta^2 = .06$	Back: Rotation angle*group: $p = .022$, $\eta^2 = .04$
		Palm	$p = .822$, $\eta^2 = .00$	
	Number of errors	Back	$p = .005$, $r = -.35$	–
		Palm	$p = .051$, $r = -.25$	
Action planning	% Comfortable end positions in critical trials		$p = .016$, $r = -.30$	–
Rapid online control	Movement Time		$p = .139$, $\eta^2 = .03$	–

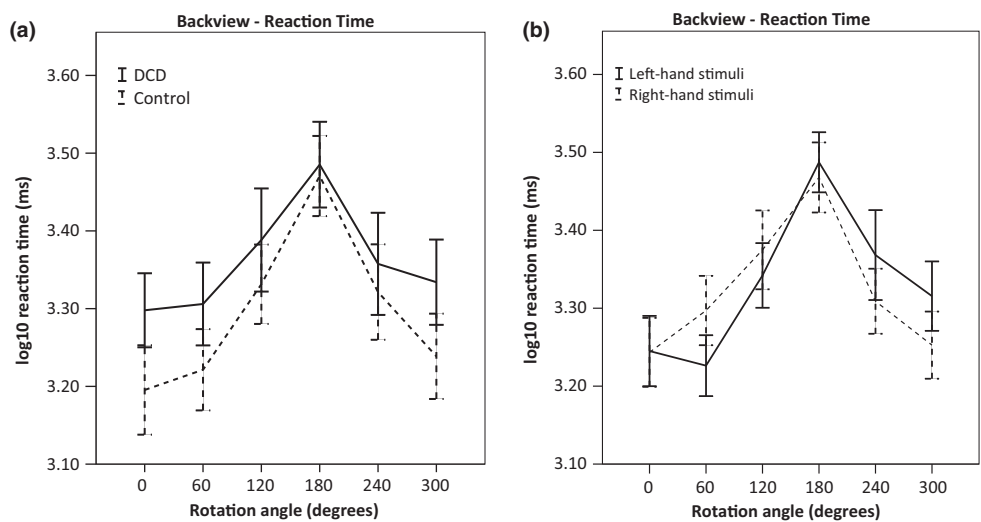


Figure 2. (a) Mean response time (RT) per rotation angle for hand stimuli in back view. Solid line refers 28 to developmental coordination disorder (DCD) group, and dashed line, to control group. (b) Mean response time (RT) per rotation angle for hand stimuli in the back view for both DCD and control group. Solid line refers to left-hand stimuli, and dashed line, to right-hand stimuli. Error bars represent 95% CI.

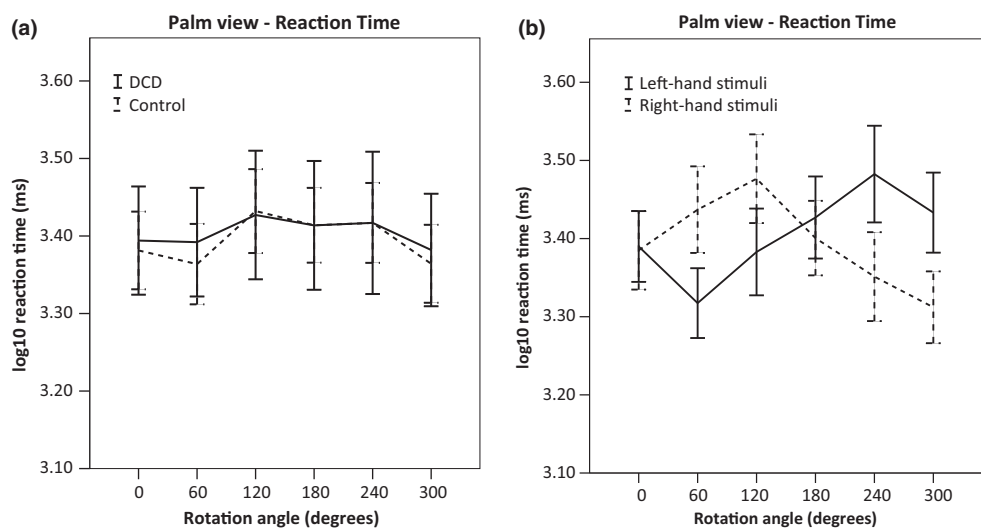


Figure 3. (a) Mean response time (RT) per rotation angle for hand stimuli in palm view. Solid line refers 29 to developmental coordination disorder (DCD) group, and dashed line, to control group. (b) Mean response time (RT) per rotation angle for hand stimuli in the palm view for both DCD and control group. Solid line refers to left-hand stimuli, and dashed line, to right-hand stimuli. Error bars represent 95% CI.

right-hand stimuli interaction, $F(5, 305) = 5.82, p < .001, \eta^2 = .09$, that did not differ between groups ($p = .71$). In line with this interaction, Figure 2b shows that RTs for hand stimuli that were rotated medially were significantly faster than the RTs for hand stimuli that were rotated laterally.

The 2 (groups) \times 6 (rotation angle) \times 2 (left/right-hand stimuli) ANOVA for the palm view showed that there was no significant difference in RTs between groups ($p = .822$), see Figure 3a. RTs significantly differed per rotation angle, $F(4.19, 255.56) = 3.93$, $p = .004$, $\eta^2 = .06$. There was no significant difference in RTs between left- and right-hand stimuli ($p = .202$). The interaction rotation angle*left/right-hand stimuli was significant, $F(3.88, 236.58) = 13.71$, $p < .001$, $\eta^2 = .18$, and did not differ between groups ($p = .54$), again indicating the RTs for hand stimuli rotated medially are significantly faster than for hand stimuli rotated laterally (see Figure 3b).

The RTs of lateral (mean of RT on 60 R, 120 R, 240 L, and 300 L) and medial (mean of RT on 60 L, 120 L, 240 R, and 300 R) stimuli were compared with a 2 (groups) \times 2 (lateral/medial) repeated-measures ANOVA for both back and palm view conditions separately. Results show a trend that RTs of the DCD group were larger than RTs of the control group, $F(1, 61) = 3.39$, $p = .070$, $\eta^2 = .05$. The RTs for laterally rotated hand stimuli were significantly larger than the RTs for medially rotated hand stimuli, $F(1, 61) = 20.46$, $p < .001$, $\eta^2 = .25$. The interaction group*lateral/medial was not significant ($p = .423$). In the palm view, there was no significant effect of group ($p = .78$). The RTs for lateral stimuli were again significantly larger than the RTs for medial stimuli, $F(1, 61) = 36.21$, $p < .001$, $\eta^2 = .37$. The interaction group*lateral/medial interaction was not significant ($p = .26$).

The total number of errors was analysed with a Mann–Whitney U -test for back and palm view conditions separately. In the back view, the DCD group made significantly more errors than the control group (DCD median = 5.0, control median = 2.0), $U = 294.00$, $p = .005$, $r = -.35$. In addition, for the total number of errors for lateral rotated stimuli shown in back view, there was a trend that the DCD group made more errors than the control group (DCD median = 2.0, control median = 0.00), $U = 374.50$, $p = .080$, $r = -.22$, while there was no difference in the number of errors when medial rotated stimuli were shown ($p = .51$). In the palm view, there was a strong trend that the DCD group made more errors than the control group (DCD median = 5.0, control median = 2.0), $U = 354.00$, $p = .051$, $r = -.25$. Furthermore, for the total number of errors for lateral rotated stimuli shown in palm view, there was a trend that the DCD group made significantly more errors than the control group (DCD median = 3.0, control median = 1.0), $U = 368.50$, $p = .076$, $r = -.22$, but there was no difference in the number of errors when medial rotated stimuli were presented ($p = .30$).

Anticipatory action planning

For the sword task, Mann–Whitney U -test revealed that in critical trials, the control group ended more often in a comfortable end position than the DCD group (median DCD = 16.67%, median control = 50.0%), $U = 362.5$, $p = .016$, $r = -.30$. In non-critical trials, the median percentage of trials, where participants ended in a comfortable way, did not differ between groups (median DCD = 100.0%, median control = 100.0%), $U = 472.5$, $p = .217$, $r = -.15$.

Rapid online control

Because MT and TT were not normally distributed, both MT and TT were transformed using a log10 transformation. The 2 (group) \times 2 (condition) repeated-measures ANOVA on MT revealed that although the DCD group had larger MTs on both non-jump (DCD $M = 933.50$, control $M = 846.40$) and jump trials (DCD $M = 1492.74$, control

$M = 1385.15$), there was no main effect of group, $F(1, 64) = 2.24, p = .139, \eta^2 = .03$. MTs of jump trials were significantly larger than MTs of non-jump trials, $F(1, 64) = 135.26, p < .001, \eta^2 = .679$. The interaction group*condition was not significant ($p = .781$). The 2 (groups) \times 2 (conditions) repeated-measures ANOVA on TT also showed no significant effect of group, $F(1, 64) = 2.64, p = .109, \eta^2 = .04$. TTs on jump trials were significantly larger than TTs of non-jump trials, $F(1, 64) = 157.08, p < .001, \eta^2 = .71$. The interaction group*condition was not significant ($p = .69$). Two independent t -tests were used to test whether the difference between jump and non-jump MTs (MT_{diff}) and TTs (TT_{diff}) were different between groups. Both t -tests showed that there was no significant difference between either MT_{diff} or TT_{diff} between groups. The Mann–Whitney U -test revealed that there was no difference in the number of CTEs in jump trials between the DCD and control group (DCD: median = 2.00, control, median = 2.00). The mean path lengths on jump trials were not significantly different between DCD and control group (DCD $M = 31.8$ cm, control $M = 30.9$ cm), $t(64) = 0.83, p = .41$.

Discussion

The aim of our study was to test the IMD hypothesis in DCD using converging operations, administered to children who were screened using strict clinical criteria. We examined different aspects of predictive motor control using three paradigms: a motor imagery, an action planning and an online control paradigm. The results showed that children with DCD performed poorly on the test of implicit MI (the hand rotation task). Performance on the action planning task was also compromised in DCD, but not that for the ROC task. Collectively, these results provide evidence that children with DCD manifest deficits in the internal modelling of movements but that task-related factors constrain their expression, particularly those factors related to movement complexity. These results extend previous studies on predictive control in children with DCD. Below, we discuss performance on each task in turn and then reconcile the overall pattern of findings by examining key task-related factors like response complexity.

Results for the hand rotation task showed that the children with DCD were able to use motor imagery, as evidenced by increased reaction times to laterally rotated compared with medially rotated hand stimuli, a pattern consistent with the biomechanical constraints of real movements. However, children with DCD were slower and less accurate than their peers, and the trade-off between response time and rotation angle was weaker. These results confirm previous studies using the hand rotation task (Deconinck *et al.*, 2009; Williams *et al.*, 2006, 2008, 2013; Wilson *et al.*, 2004). This pattern of performance suggests that motor imagery can be enlisted by children with DCD, but more slowly and less accurately than controls. From this task, we infer that there exists a basic ability in these children to represent internally the spatial and temporal coordinates of a prospective action (internal modelling), but that it is less well developed than is typical for age. The general slowness and reduced accuracy fits a profile of developmental lag seen in other cognitive abilities including working memory, attention, and response inhibition (Diamond, 2013; Wilson *et al.*, 2013).

Performance on the action planning task was compromised in DCD, indicating reduced forward planning in these children. The DCD group ended less often in a comfortable end position during critical trials compared with typically developing children (Smyth & Mason, 1997; van Swieten *et al.*, 2010). In an earlier study by van

Swieten *et al.* (2010), it was shown that children with DCD were biased towards selecting the simplest initial movement, while Smyth and Mason (1997) found no difference in grip selection between DCD and control groups. These different findings probably reflect differences in screening and severity of DCD. Smyth and Mason (1997) used a m-ABC percentile cut-off score of <15th and did not check for DSM-IV Criterion B (interference of motor problems with daily life or academic achievement) or Criterion D (motor problems not explained by a medical/neurological disorder). van Swieten *et al.* (2010) recruited children from a hospital and diagnosed DCD by a history of coordination problems and a m-ABC cut-off <5th percentile. As such, there were more severe cases of DCD in this study compared with Smyth and Mason (1997). Our study used strict DSM criteria, with results similar to van Swieten *et al.* (2010). This shows clearly that severity of DCD is an important factor when reconciling competing findings across studies of action planning, with the more severe cases showing greater deficit, indicative of problems in internal modelling. Finally, task complexity is also a factor in forward planning, as shown by Noten *et al.* (2014); here increased task complexity led to a breakdown in motor imagery ability in a group of mild DCD (using research criteria). In sum, deficits in action planning are evident in DCD, but may only manifest in more severe cases of DCD, and with more complex task constraints.

In the present study, we did not find a specific deficit in DCD with online control, as measured using the ROC task. This result accords with Plumb *et al.* (2008) who showed no selective impairment on jump trials in a severe DCD group (aged 7–13 years), but rather a generalised slowness in reaction and MT. By comparison, deficits in online control were detected in four studies using the same paradigm (Hyde and Wilson 2011a,b, 2013; Fuelscher *et al.*, 2015). The main distinction between studies concerns the screening instrument: Hyde and colleagues used the McCarron Assessment of Neuromuscular Development (MAND; McCarron, 1997) rather than the m-ABC, with the DCD group comprising children between 7 and 12 years and a MAND NDI <10th or ≤15th percentile. Five of the ten items on the MAND assess fine motor skill, while only three of eight items do so on the m-ABC. Indeed, it is known that a significant level of independence exists between the MAND and the m-ABC (Brantner, Piek, & Smith, 2009). Other work shows the MAND to be a very sensitive measure when screening for DCD (Tan, Parker, & Larkin, 2001). On balance, the MAND is likely to identify the children with DCD who tend to be more impaired on fine-motor items than comparable tests. Because the ROC task requires hand movement, screening using the MAND is more liable to identify the children whose internal modelling processes are selectively impaired for tasks that enlist manual action and fine-control of the digits. Another difference between the present study and those of Hyde and Wilson (2011a,b, 2013; Fuelscher *et al.*, 2015) is that children in our study were constrained to only make movements in 2D and not movements in flight (or 3D). Our task had reduced spatial complexity as movements only needed to be made in the transversal plane. It is well known from the motor control literature that fewer degrees of freedom in movement reduce task complexity (Bernstein, 1967). In fact, children with DCD enlist this ‘strategy’ (reduce the degrees of freedom) when faced with tasks that are a challenge to them or avoided like two-handed ball-catching task (Utley, Steenbergen, & Astill, 2007). ROC tasks with movements in 2D space have been extensively used in earlier studies (Henis & Flash, 1995; van Sonderen *et al.*, 1989). MTs in our study are longer than those of Hyde and Wilson (2011a,b, 2013; Fuelscher *et al.*, 2015), but comparable to Plumb *et al.*, 2008. Taken together, we hypothesise that children with DCD show impaired online control for movements of shorter duration (approximately 500–900 ms). But for tasks that are adapted or simplified (and that entail longer movement durations, approximately

900–1,500 ms), deficits in online control are less evident. Our results suggest some modifications to current theories on DCD generally, and the IMD hypothesis more specifically: results appear to clarify the task conditions under which children with DCD show deficits in fast online control, and those conditions where slower feedback processes suffice.

In sum, when comparing our results to those of earlier studies, several intriguing methodological and paradigmatic factors may explain the differences in findings. Selecting a DCD group based on less stringent research criteria will tend to reduce the severity of the DCD sample, and conceal group differences. When more stringent clinical criteria are used (with strict reference to DSM criteria), differences between DCD and control group tend to be more pronounced – this effect applies to not only skill performance, but also the neurocognitive bases of motor control. Another important factor is the choice of motor screening tests. Use of the MAND will tend to yield a DCD sample that is more specifically impaired on fine-motor skills, compared with use of the m-ABC. This also may influence group comparisons on paradigms that enlist manual action, like the ROC. Finally, even subtle differences in task complexity between studies can affect the pattern of deficits observed. Poor predictive control appears to be more evident for complex task constraints, like the 3D version of the ROC task.

Collectively, the present study is the first to perform a within-subject assessment of motor imagery, action planning, and ROC in a group of children that meet strict DSM-V diagnostic criteria for DCD. There is sufficient evidence to support the hypothesis that children with DCD are compromised in the ability to enlist internal modelling as a control solution in the performance of goal-directed or simulated action; this was evident on motor imagery and action planning tasks. For the ROC tasks, our results show that even with what appear to be subtle distinctions in task presentation, complexity, or familiarity can alter the pattern of performance. These results have important implications for the design and reporting of future neurocognitive studies of DCD, where precision and systematic variation of these factors is critical to advance the field. They also underline the specificity in learning that exists in DCD at the level of motor skill development and motor control. Understanding the nuances of this effect across the DCD spectrum will contribute valuable insights for theory and the design of tailored intervention programmes.

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Received 30 April 2015; revised version received 28 October 2015